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Multifunctional Environmental Energy Tower: a case study of an innovative system for renewable energy exploitation

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Abstract

In a context of increasing interest in energy efficiency, the attention to the environmental quality is bringing the city of the future to be structured on energy smart grids for electricity, heat and natural gas production and distribution. The Multifunctional Environmental Energy Tower intends to be considered as a node in the future Smart Grid of the borough "Rome EUR", to decrease the primary energy consumption from fossil fuels, to reduce greenhouse gas emissions and to maximize the energy production from renewable sources, as required by the European Union objectives at 2020. Renewable energy generation systems are integrated in a single vertically developed building, where energy is mainly produced from waste in integration with thermal and electrical energy storage systems, to create an intelligent tower combining and meeting together energy demand and supply.

This integrated system allows to overcome some problems related to the renewable energy sources usage: their non-programmability, the land occupation and consumption, the social acceptance and the imbalances in the electricity grid. The designed building produces electricity for the grid, ensuring the air conditioning for Acea's company utilities and to feed the existing heating district network located in "Torrino-Mezzocammino" district within "Rome Eur" borough.

The architectural components were designed to link the architectural view and the functional aspects, because its location within the roman roads net developing from the "Grande Raccordo Anulare" (GRA) the tower is configured as a totem of energy efficiency and technological innovation.

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Keywords: Renewable Energy Sources, Smart Grid, Energy Efficiency; Architecture, Dynamic Simulation;

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Nomenclature

ETS	Emission Trading System
CRB	Biomass Research Centre
OFMSW	Organic Fraction of Municipal Solid Waste
GRA	Grande Raccordo Anulare
LED	Light Emitting Diode
DM	Dry matter
WW	Wet weight
COP	Coefficient Of Performance

1. Introduction

Renewable energy sources can contribute significantly to energy production in a low-carbon and fossil free contest, to serve the several activities of the city such as the residential areas, services, transport, business and manufacturing boroughs .

A new city structure will be shaped on energy efficiency, technological innovation and environmental sustainability: these are the themes behind the "Smart City" concept. The reduction of energy consumption and the increased use of energy from renewable sources, together with the energy efficiency increasing, constitute the main goals as defined in the European Union package on Climate Change.

The recent regulation for environmental objectives formalized in 2030 by the EU introduces a new target of greenhouse gas emissions reduction by 40% compared to the 1990's emissions to be shared between the ETS and non-ETS sector [1].

Therefore, today, 54% of the world's population lives in urban areas, this proportion is expected to increase to 66% by 2050. Projections show that urbanization combined with the overall growth of the world's population could add another 2.5 billion people to urban populations by 2050 [2].

The definition of strategic objectives for 2030 in terms of energy efficiency and renewable energy development is still in progress; the targets set for 2020 are actually ongoing [3].

The renewable energy development runs together with the overcoming of the critical points related to their usage as the reduction of costs, land consumption and footprint [4], their non programmability, the social acceptance [5] and it requires the development of an integrated system for electrical and thermal energy production, storage and distribution, flexible and equipped with renewable energy technologies [6] into a single building structure: the Multifunctional Environmental Energy Tower [7], a node of the Smart City grid.

2. Multifunctional Environmental Energy Tower

The Multifunctional Environmental Energy Tower, designed by the CRB, Biomass Research Centre of the University of Perugia [8] is the result of the research integration of different technologies for renewable energy production [9,10].

The tower integrates and optimizes energy production from several renewable energy sources: a photovoltaic roofing and coating, a geothermal system integrated to foundation piles and a bio-digester set inside the stem of the tower, fed with the OFMSW - Organic Fraction of Municipal Solid Waste, harvested from the surrounding area and stored in a underground tank.

The tower is equipped with a weather forecasting unit to monitoring and predict the variation of weather and environmental conditions and to define strategies for energy production and accumulation also depending on the energy needs by utilities. Storage systems (electric battery and water storage tank) and energy production plants are differentially synchronized to increase efficiency.

The case study site where the tower has been designed is owned by Acea, and it is adjacent to the Tiber river and it is located within the Rome Eur borough in Torrino-Mezzocammino district (Fig. 1) in the south of Rome and close to major roads: the GRA, Via del Mare, the highway to the Fiumicino airport (Fig. 2). The site includes: the Acea thermal power station for the district heating and for the electricity production and a wastewater sewage treatment plant. The utilities are represented by the Acea buildings where the offices and control room are located, workshop and laboratories and a conference hall.

The tower will power at first these buildings and the residual thermal energy is addressed to the district heating network of the area Torrino-Mezzocammino (Fig. 1).

Fig. 1: The case of study area.

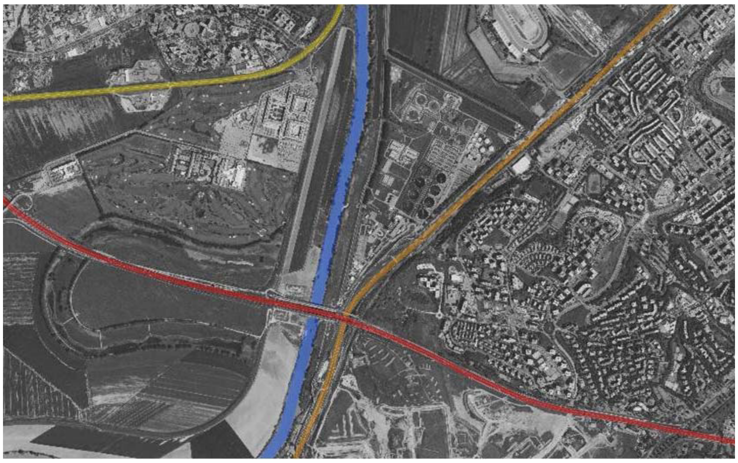

Fig. 2: Major roads bordering the intervention area.

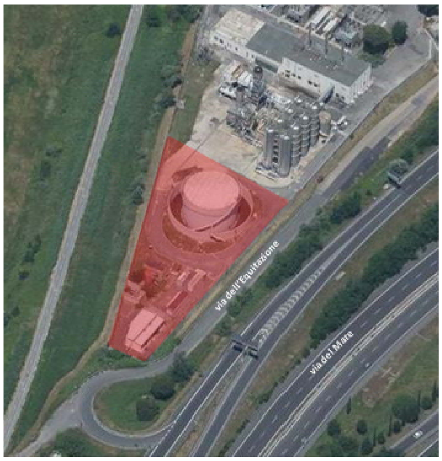

Fig. 3: The Acea site.

3. The architectural design

Given the large scale of the tower, its architectural design was not neglected and all the components are combined with their functional role, fundamental to improve a prototype composed by several energy production systems integrated each other. The purpose of the proposed project is to confer to the tower a symbolic mark of "energy efficiency and technological innovation" totem: a building visible from the main roads bordering the case of study site, in particular the GRA (Fig. 3). Moreover the site is currently occupied by disused tanks of diesel 20 m high and in a logical of redevelopment of the area, it maintains the presence of technological vertical extended structures.

The communication technology assumes important roles in architectural space and the image becomes the backbone; for example Bayer or Venturi in the 60's considered architecture as a symbol in the urban context and not just only a form in the space: buildings become huge billboards in which images are sliding and insert big written or corporate logos; become alive and active, communicating using their "new skin" [11].

The energy tower will be placed in the Acea site with a communicative intent, ensuring its perception by the GRA during the day and night. An extended radius of GRA crossing the project area connects the road with the site creating a directional axis perpendicular to the highway (Fig. 4 a). According to this arrangement a grid with square modules (2m x 2m) is plotted defining a certain direction for the tower perception (Fig. 4 b). This grid is integrated with the surrounding area reproducing the existing urban fabric (Fig. 4 a). The grid is divided into three bands identifying areas for a specific usage: the first part is a green area provided with bio-filters for gaseous emissions; the second takes place for the tower positioning and the third for all the technological systems and features (Fig. 4 c).

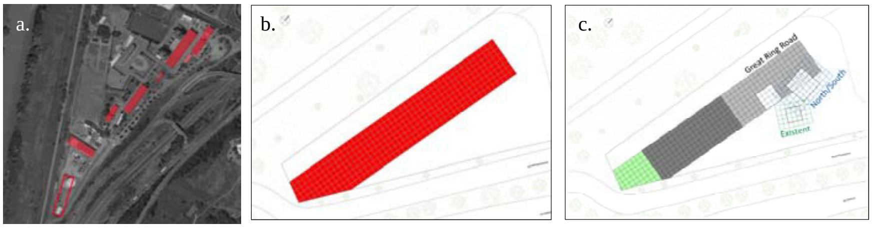

Fig. 4: Logical path composition: the radius (a), the grid (b) and the bands (c).

The tower plan is 10 meters squared and it is 35 m high. A technical space is located in the ground floor; the two underground tanks are closed by a steel plate located at the ground level with an automated opening to be loaded and empted respectively in bio-waste and digestated matter. The grid will be marked by a paving made in reinforced concrete plates; in plan the tower and its storage tanks intend to imitate, in both shape and colors, the Acea logo (Fig. 5 a). The skin of the tower is made by translucent polycarbonate panels integrated with photovoltaics modules. The translucent coating has also excellent thermal insulation properties, a high value of light transmission and high resistance to weather. The pictures below (Fig. 5 b) reproduce the rendering of the tower and its skyline.

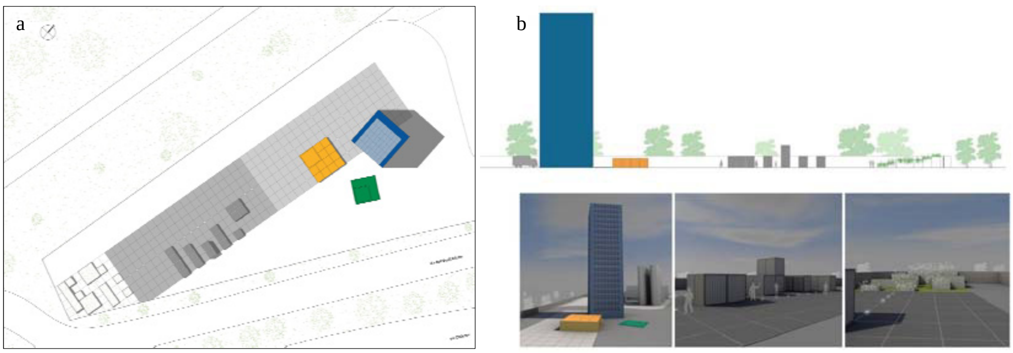

Fig. 5: (a) Plan of the Acea site; (b) Elevation and render of the Acea site.

During the day the totem of the tower for the renewable energy production is empathizes by color combinations; after sunset there are lighting effects by a series of LED steps-marks set at the intersections of the grid combined with LED strips along the frames of the facade all over the tower whose color code varies by the several weather conditions (Fig. 6).

Fig. 6: A rendering of the tower.

4. The heating and cooling dynamic simulation

The thermal requirements of the buildings were calculated using a dynamic simulation tools i.e. Design Builder combined with Energy Plus.

The first building is a two floor space where the control room is located.

The second building is composed of two main parts:

- a mechanical laboratory;
- a two floors space, hosting two laboratories and a couple of offices.

For both of the two buildings a complete set of energy simulations were run. The initial proper conditions (concerning the geometries, the envelope relevant features, the conditioning systems) were considered. In addition, the comfort conditions were imposed for all the spaces.

The results of the simulations have shown in the following. For the first building, considering the winter conditions, the maximum energy consumption was equal to 1143.7 kWh and the power peak was equal to 110 kW. For the same building, considering summer conditions, the maximum energy consumption was equal to 1633.2 kWh and the power peak was equal to122 kW.

For the second building, considering the winter conditions, a maximum energy consumption of 122.9 kWh and a power peak equal to 15 kW were calculated; while for summer conditions, a maximum energy consumption of 55.9 kWh was calculated and the corresponding power peak was equal to 5 kW.

Figures 7-9 show the required thermal power trend as a function of the time for both heating and cooling conditions and for both the investigated buildings.

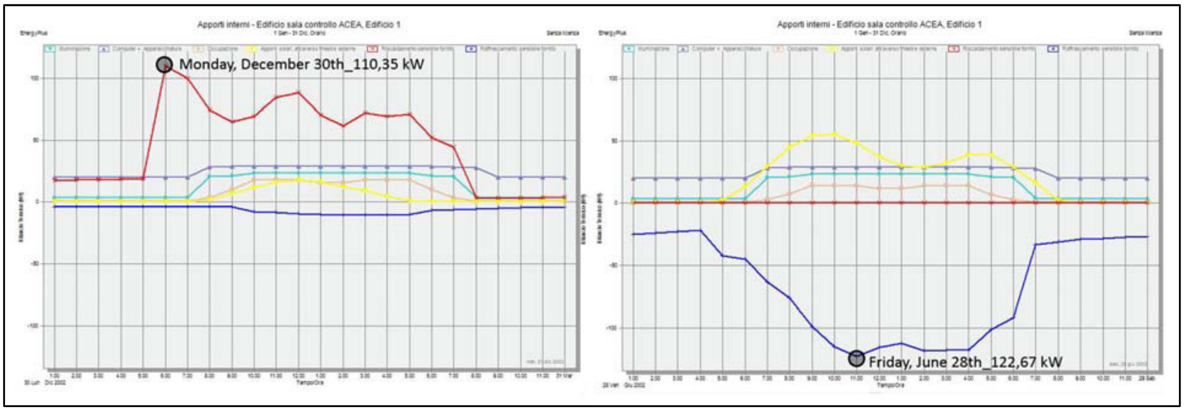

Fig. 4: Required thermal energy for both heating and cooling conditions (First building).

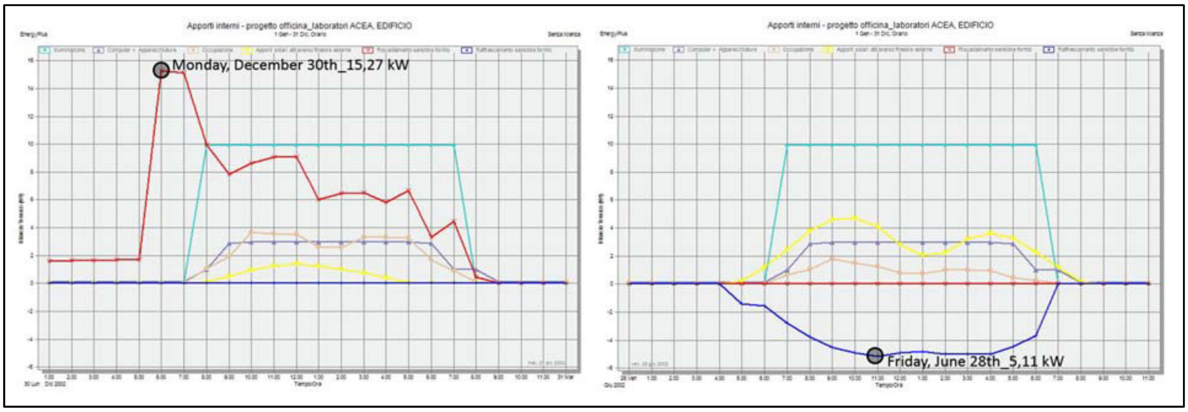

Fig. 5: Required thermal energy for both heating and cooling conditions (Second building).

5. The tower plant design

The equipments placed on the tower are: the photovoltaic panel, the anaerobic reactor for biogas production and a geothermal plant integrated with the foundation piles.

The biogas plant is fed in co-digestion by a mix of biomass (as defined by national regulation [12]) composed by OFMSW from the Torrino-Mezzocammino district (35,000 inhabitants) and sewage sludge recovered from the nearby Acea wastewater treatment plant serving the south of Rome area. The OFMSW production is about 24 tons per day; assuming the organic percentage in 40% of the total waste, biomass is harvested through a three times a week curbside collection [13], operated by a small truck shuttling with a transference station. The sewage slurry is carried through an underground pipe by the wastewater plant site is about 30,000 tons per year.

The table below summarizes the total biomass flows and its characteristics (Table 1) [14,15,16].

Table 1. Biomass characteristics.

Biomass	Quantity [tons/year]	DM [%]	Biogas yield [Nm^3/ton WW]	Biogas [Nm^3/year]
OFMSW	8,700	35-45	200	1,740,000
Sewage sludge	30,000	19	38	1,140,000

Due to the DM content of the mixed biomass (about 23%), the typology of the anaerobic digestion was chosen: when the solid content exceed 20%, the best process with high yield in biogas and reduced retention times is represented by the Dranco system with a single-stage process [17,18] inside the 1,810 m^3 cylindrical digester installed inside the stem of the tower. At the bottom of the tower a 1 MW powered engine is fed by the biogas produced by the waste; the thermal power is 1.1 MW [19]. The scheme of biomass plant is shown below (Fig. 9).

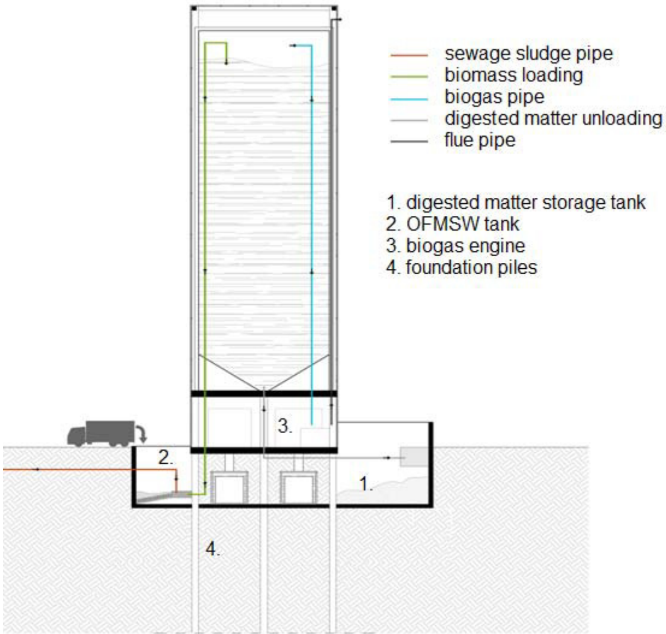

Fig. 6: Functional scheme of the tower.

Assuming 60W/m of soil thermal yield [20,21], the 30 meters long geothermal closed loop piping integrated to the five foundation piles is designed to cover thermal losses from the anaerobic digester (4.5 kW), considering a digester thermal transmittance of 0.10 W/m^2K. The coupled heat pump is 8 kW thermal powered with a COP – Coefficient Of Performance of 4.8. Furthermore, the plant will be integrated with thermal storage systems via underground tank filled with rainwater in which are placed heat exchangers.

The photovoltaic system is integrated with a lithium ion battery [22,23] and converts solar energy into electricity to feed all the mechanical equipment of the digester: waste and sludge loading, mixing, grinding etc. and to supply the heat pump. The unused energy will be injected to the grid. The panels are placed over the tower roofing and on the south-facing facade of the tower. The values of annual solar radiation on the roof and facade were calculated using a spreadsheet setting the geographical location and other parameters related to the placement of photovoltaic modules. The system consists in 200 modules, 40 on the roof and 160 in the facade, for a total peak power of 49 kW [24].

6. Economics

Tables below (Tables 2, 3, 4) summarizes all the economics of the proposed idea.

The most relevant revenue is attributable to the electric energy selling from biogas combustion as in the current decree: the 20 years incentive for electric energy is defined as the sum of the basic fee of 0.256 € per kWh and the additional fee of 0.04 € per kWh for the cogeneration system [25]. Another opportunity is given by the recent regulation in biomethane [26]: the upgraded biogas can be injected to the methane grid or used as fuel in cogenerating plants or to feed vehicles in refilling stations. This economic scenario will constitute a further development of this work.

Revenues are also referred to heat sold at the price of about 0.07 € per kWh, defined by the convention of the user's cost for self production and the revenues for heat transfer. The organic waste is conferred by the municipal manager at the tower tank and its disposal is paid 50 €/tons: the fourth item of the current total disposal costs.

The estimated payback period is around the 6th year.

Table 2. Capital expenditure.

Tower building	1,000,000 €
Mechanical components and renewable plants	4,600,000 €
Equipment & fleet	500,000 €
Subtotal	**6,100,000 €**
Financing costs of the invested capital	366,000 €
Total investment costs	**6,466,000 €**

Table 3. Operating expenditure.

Variable costs: waste disposal, assurances, maintenance service and fuel	135,000 €/y
Personnel costs	195,000 €/y
Administrative costs	80,000 €/y
Total operative costs	**410,000 €/y**

Table 4. Revenues.

Revenues on waste disposal	435,000 €/y
Revenues on heat to the district heating network	175,000 €/y
Revenues on electricity from biogas	1,820,000 €/y
Total revenues	**2,430,000 €/y**

7. Conclusion

The proposed OFMSW management is an example of a completed pathway: waste is produced by the nearby residential area of Torrino-Mezzocammino, whose people received heat via the district heating by the waste energy enhancement. Environmental savings are expressed in terms of reduction of natural gas consumption and the consequent greenhouses gas emissions: about 600 tons CO_2 per year.

The proposed idea is characterized by a vertical extension due to increase the high energy density, up to 2 MW in 500 m^2 surface, and to reduce the environmental footprint. In addition, a vertically extended structure can be inserted easily into the existing city allowing to create an integrated smart grid gradually replacing the old energy net.

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